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Review paper on solar-powered air-conditioning through adsorption route

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ABSTRACT

Solar-power based sorption refrigeration systems do not suffer from the problem of greenhouse gas emission and release of ozone layer depleting substances as in the case of conventional vapour compression refrigeration system. Absorption based systems are already commercially available while adsorption based systems are still in research and development stage. Progress and development of solar-powered adsorption cooling systems have been described in this paper. Factors preventing commercialization of this system have been discussed in detail. The state of the ongoing research, to make the system more efficient and cost effective, has been presented.

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1. Introduction

The demand for human comfort is increasing day by day. The International Institute of Refrigeration in Paris has estimated that approximately 15% of all the electricity produced in the whole

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world is employed for refrigeration and air-conditioning processes of various kinds, and the energy consumption for air-conditioning systems has recently been estimated to be 45% of the whole households and commercial buildings. Most of this demand is being met by vapour compression based refrigeration system. Recently, though nominal, some vapour absorption based refrigeration systems have come for industrial and office building use.

The conventional vapour compression machines consume a lot of electrical energy, which lead to depletion of the precious fossil fuel resource as well as production of lot of greenhouse gases. Most of the refrigerants in use cause ozone layer depletion, some having high greenhouse gas emission also. Montreal and Kyoto Protocol have put ban on the ozone layer depleting and green house gas producing refrigerants, CFCs, HCFCs and HFCs.

Solar energy can be used for air-conditioning in two ways – electricity through solar photo-voltaic cell and then using the same in conventional i.e. vapour compression cycle and the heat driven sorption system. The improvement in solar photo-voltaic cell efficiency is very slow and so initial cost is very high till now. Among the heat driven systems, vapour absorption systems are already commercially available, but mostly having capacity of more than 30 TR. They have limitations for smaller capacity.

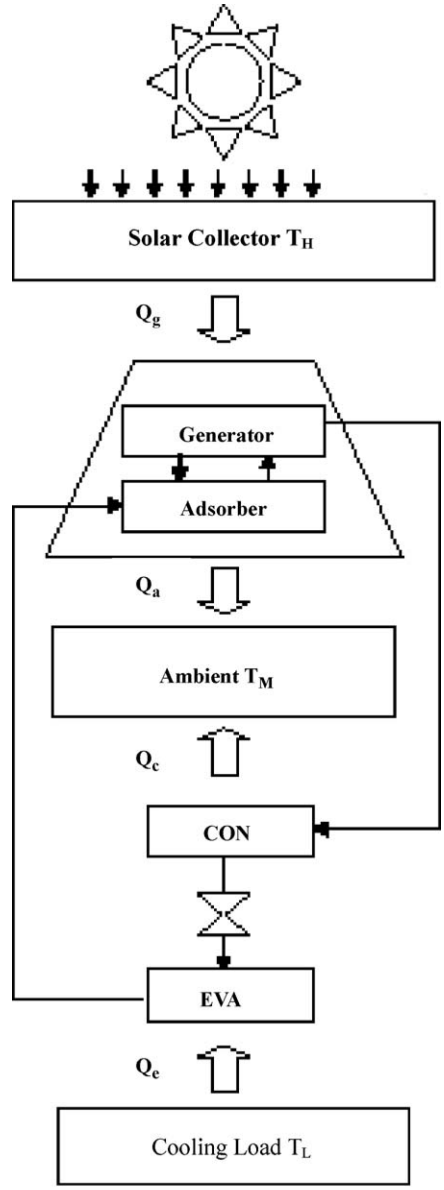
Adsorption based systems may fill this gap in replacing high electrical energy and thereby fossil fuel consuming as well as environment polluting vapour compression systems. Even if 50% of present market of small AC systems can be replaced by solar-powered adsorption system, a considerable worth of electrical energy can be saved and a good amount of carbon credit can also be earned.

Natural refrigerants of the adsorption system have zero ozone depletion potential and zero global warming potential. Adsorption systems are compact and noise free; less sensitive to shocks and to the installation position. They do not require frequent replacement of adsorbent. They have very less rotating parts, no refrigerant/adsorbent pump and so very minor maintenance/service issues. Corrosion, crystallization problems are not there like in absorbent systems. Flexibility in regeneration temperature for part load operation is much more than that in absorption systems.

Considerable amount of research is being carried out on a number of adsorbent–adsorbate pairs like zeolite–water, activated carbon–ammonia, activated carbon–methanol and silica gel–water etc. Among the pairs, silica gel–water system is ideal for solar energy utilization due to its low regenerating temperature. Zeolite–water pair requires a regeneration temperature of above 200 °C, activated carbon–ammonia pair also requires more than 150 °C for its regeneration. These temperatures are not obtainable by simple flat plate or evacuated tube solar collector systems. Activated carbon–methanol pair also works at low regeneration temperature but it is more suitable for ice production and freezing application. Water, having a higher latent heat of vapourization and suitable for producing a chilled water temperature of 8–10 °C, is a more correct choice for air-conditioning purpose.

2. The process

Adsorption is a process resulting from the interaction between a solid (adsorbent) and a gas (refrigerant), based on a physical or chemical reaction process. The adsorption process concerns separation of a substance from one phase, accompanied by its accumulation or concentration on the surface of another. An adsorption refrigeration machine utilizes the phenomenon of physical adsorption between the refrigerant and a solid adsorbent; the molecules of the refrigerant come to be fixed at the surface of adsorbent via connections of the type Van der Waals [1].



A Schematic Diagram of Adsorption Cooling

When fixed adsorbent beds are employed, which is the common practice, these cycles can be operated without any moving parts. On the one hand, the use of fixed beds results in silence, mechanical simplicity, high reliability and a very long lifetime, on the other hand, it also leads to intermittent cycle operation, with adsorbent beds changing between adsorption and desorption stages, which decreases the COP of the system. Hence, when constant flow of vapour from the evaporator is required in order to provide continuous cooling, two or more adsorbent beds must be operated out of phase.

According to Polanyi theory [2] the adsorption equilibrium relation for a given adsorbent/adsorbate system can be expressed by using the adsorption potential (ε). Thus:

$$\varepsilon = RT\ln\left(\frac{Ps}{P}\right)$$

where Ps is the saturated pressure of liquid adsorbate at the adsorption temperature T, and P is the pressure of the adsorbate vapour in equilibrium with the adsorbed liquid film, and R is the universal gas constant.

A detailed analysis of the thermodynamics of adsorption and its different isotherms are given by Leite [3].

Heat transfer problems in adsorption cycles systems have been intensively investigated by Cacciola et al. [4]; the experience shows that two main resistances dominate the transfer of heat the external thermal vector fluid to the adsorbent bed:

(1) the first one occurs at the metal–adsorbent interface and depends on the physical contact between the materials and
(2) the second resistance is associated with heat transfer inside the solid adsorbent bed and it is inversely proportional to the effective conductivity.

It has been reported by Tather et al. [5] that an optimum compromise should be achieved between the high porosity necessary for fast vapour diffusion and the high density required for good thermal conductivity.

3. A brief history

The history of solar adsoption system dates back to 1920s when sulfur dioxide and silica gel were used for the air-conditioning of railway carriages in the USA [6]. But with the development of cheap reliable compressor and with the introduction of CFCs, heat based sorption systems took a back seat. After the oil crisis in 1970s and with the restrictions imposed by Montreal (1987) and Kyoto (1997) protocol, research again started on heat driven sorption cooling systems. The development of sorption refrigeration systems powered by solar energy emerged in the late 1970s, following the pioneering work of Tchernev [7], who observed that a naturally occurring mineral, called zeolite, adsorbs large amounts of water vapour when cooled and desorbs the water vapour when heated, thus providing a unique opportunity for its utilization in refrigeration applications.

Tchernev studied a basic solid sorption cycle with the working pair zeolite–water; he fabricated and tested a 100 dm^3 zeolite–water solar energy powered refrigerator. The collector/generator/absorber component contained 5 cm thick, 50 kg of zeolite per square meter. For a solar energy input of 6 kWh, the refrigerator produced 900 Wh of cooling per square meter of collector area with a coefficient of performance (COP) of 0.15 [8]. A demonstration unit of a refrigerator was first commercialized by Tchernev by using zeolite–water system. Successful field testing of this unit sparked interest world wide. However, natural zeolites are difficult to obtain in sufficient quantities in many countries. Consequently synthetic zeolite, particularly molecular sieve 13×, which are easily manufactured, are commonly used.

4. State of the art – eighties

4.1. Solar ice makers

Dupont et al. [9] investigated two solar-powered solid adsorption refrigerators: one utilizing a water cooled condenser, while the other used an air cooled condenser. The working pair for both is zeolite 13×–water. Test results showed that in the water cooled condenser model, the solar COP varied over the range 0.04–0.14 with ice production in the range 3.71–8.14 kg/m^2 of collector area. For the air coded condenser refrigerator, the solar COP of 0.10 was achieved with 7.0 kg/m^2 of ice produced.

Pons and Guilleminot [10] developed a prototype with the pair activated carbon–methanol. This machine produced almost 6 kg of ice per square meter of solar panel when the insolation was about 20 MJ per day with a solar COP of 0.12. They concluded that this performance could be improved by reducing the sensible heat of the evaporator, improving the cooling of the collectors and making all their collectors identical.

A modelization of a solar-powered solid adsorption cooling machine has been presented by Passos et al. [11] to conclude that the performance of the solar-powered unit depends strongly on the absorptivity of the solar collector and on its back insulation.

At LIMSI, the zeolite–water pair was chosen for refrigeration, and the active carbon–methanol pair for ice production. Pons and Grenier [12] worked on a solid adsorption pair of zeolite and water, to produce a refrigerating effect and the coefficient of performance was about 0.1. In 1986, they successfully experimented with the adsorption pair of AC and methanol.

Exell et al. [13] designed and fabricated a charcoal–methanol solar refrigerator. The net solar COP obtained was above 0.10 and sometimes reached 0.123. The maximum evaporator temperature during most nights was below −7 °C, but during some nights it was as low as −12 °C. The refrigerator was able to manufacture up to 4 kg ice after a clear day.

4.2. Solar air-conditioners

Grenier et al. [14] built a large cold store of volume 12 m^3 powered by solar energy using a zeolite 13×–water combination. The evaporator temperature achieved was as low as 2.5 °C, corresponding to a solar COP of 0.086. Comparing these results with those of Refs. [8] and [9] above reveals that the technology does not show any size advantages and, therefore, could be adaptable to large, small and medium size refrigerators.

Sakoda and Suzuki [15] constructed and tested a laboratory scale closed adsorption cooling system employing a silica gel–water combination. The successful operation of this unit demonstrated clearly both the experimental and technical feasibility of solid adsorption refrigeration.

Sakoda and Suzuki [16], utilizing solar heat, presented the advantages and limitations of the simultaneous transport of heat and adsorbate in a closed type adsorption cooling system.

Kluppel and Gurgel [17] built two prototypes, one small domestic refrigerator and one portable water cooler, of solar-powered solid adsorption cooling systems using a silica gel–water combination. A solar COP of 0.055 was obtained for the small domestic refrigerator prototype with evaporator temperatures below 277 K, while it reached a COP of 0.077 for the portable water cooler with evaporator temperatures around 285 K.

Adsorption refrigerators appeared in the market in 1986 and they were produced by the Nishiyodo Kuchouki, Co. Ltd. The silica gel–water adsorption chillers produced by this company are sold in the American market by the HIJC USA Inc. This company estimated the payback of this chiller to about 2–3 years [18]. The chiller can be driven by hot water from 50 to 90 °C, and the temperature of chilled water is close to 3 °C. The COP can reach 0.7 when the chiller is powered by hot water at 90 °C.

5. State of the art – nineties

5.1. Solar ice makers

Critoph [19] built a laboratory scale activated carbon–ammonia refrigerator. The evaporator temperature attained was up to −1 °C and about 3 kg of ice was manufactured. The peak collector temperature for the simulated day tests was 115 °C, and the solar COP was 0.04. Although the COP and ice production of this machine are less than those of an activated carbon–methanol pair machine, activated carbon–ammonia system is less sensitive to small leakages, which makes it more reliable for application in remote areas where maintenance is not readily available.

However, the difficulties and practical disadvantages of activated carbon–ammonia systems are the high pressure requirement, resulting in the bulkiness of the refrigerator, and the corrosive nature of the refrigerant, ammonia. The problem of great bulk in large systems can be avoided by the development of rapid cycling units.

Critoph [20,21] studied a rapid cycling solar/biomass-powered adsorption refrigeration system with activated carbon–ammonia as working pair. The thermal COP was about 0.3 when the initial generator temperature was about 50 °C and evaporating temperature was about 0 °C. In this version, two separate adsorption cycles are operated out of phase such that when one adsorber is being heated by the energy source, the other cools to ambient temperature, readsorbing its refrigerant and producing useful cooling in the evaporator.

Performance limitations of adsorption cycles for solar cooling were formulated by Critoph [22].

Phillip et al. [23] built a flat plate solar collector operated, intermittent zeolite 13×–water refrigerator. Their system comprised a box type solar collector of surface area 0.25 m^2 containing about 5 kg of adsorbents. Evaporator temperatures as low as −8 °C could be attained with 1 kg of ice produced during the night cycle.

Headley et al. [24] built a charcoal–methanol adsorption refrigerator having a cylindro-parabolic reflector which concentrated solar heat onto an adsorbent copper tube at the focal line. It manufactured up to 1 kg of ice at an evaporator temperature of −6 °C, and the net solar COP was of the order of 0.02. The twin advantages of this refrigerator are the capacity to produce ice even on overcast days and lightness of the entire system compared to other designs. However, concentrating solar collectors are expensive and complex in structure, as they need to always track the path of the sun to capture only the direct component of solar radiation.

Wang et al. [25] presented a new hybrid of solar-powered water heater and adsorption icemaker with a solar collector area of 2 m^2 which can produce 3–8.7 kg ice/day. The COP was about 0.15–0.23 and heating efficiency of about 0.35–0.38.

In 1999, Wang et al. [26] carried out a study on solar adsorption icemaker and the experimental results reached a COP of 0.12–0.135.

Sumathy and Li [27] operated a solar-powered icemaker with the solid adsorption pair of activated carbon and methanol, using a flat plate collector with an exposed area of 0.92 m^2. This system could produce ice of about 4–5 kg/day with a solar COP of about 0.1–0.12.

The high initial costs of the machines and the low heat transfer properties of the adsorbers are among the limitations for the commercial application of adsorption systems. The use of heat pipes could help to reduce these problems, not only due to the high heat flux density provided by these devices, but also due to the lack of moving parts to drive the heat transfer medium, which makes the whole system cheaper and more reliable.

The condensation of the working fluid of the heat pipe can release the necessary heat to regenerate the adsorbent, while the vapourization of the fluid can absorb the sensible heat and the sorption heat of the adsorbent during the adsorption phase.

Meunier [28] mentioned a study carried out at LIMSI, a CNRS (French National Centre for Scientific Research) laboratory, where extremely high heat transfer coefficients of about 10 kW/m^2 were obtained with the utilization of heat pipes in adsorption systems.

Heat pipes were used in the heat transfer fluid and refrigerant circuits of the solar-electricity-powered adsorption system studied by Vasiliev et al. [29].

According to Vasiliev [30], vapour dynamic thermosyphon like the one employed in the system developed by Vasiliev et al. [31] has smaller temperature drops than conventional heat exchangers, which is favourable from the thermodynamic point of view.

5.2. Solar air-conditioner

A commercially available low temperature (80–90 °C) adsorption cooling system for air-conditioning application has been modified, using methanol/silicagel as working pair for the cold storage of agricultural products at temperatures of 2–4 °C in India. Calculation and test results showed that the COP was about 0.30 when operating the system at a chilled water temperature of −2 °C, a heating water temperature of 85 °C and a condenser temperature of 30 °C [32].

6. 2000 – onwards

6.1. Solar ice makers

Wang et al. [33,34] proposed a solar-powered continuous solid adsorption refrigeration and heating hybrid system. A solar water heater and an adsorption icemaker are joined in the same machine. The machine used the working pair activated carbon–methanol and had 2 m^2 of evacuated tube collectors to warm 60 kg of water up to 90 °C. The daily ice production was about 10 kg when the insolation was about 22 MJ/m^2.

Critoph [35] applied a heat pipe to heat and to cool the adsorber of an adsorption system. The author concluded that fluids with different physical and chemical properties should be used for cooling and heating purposes. The utilization of different fluids in this case would avoid sub-atmospheric and very high working pressure, which is desirable because it eliminates both the occurrence of possible inward air leaks and the utilization of thick material to enclose the working fluid.

Li et al. [36] performed experiments with a solar-powered icemaker that had activated carbon–methanol as working pair. This icemaker had a COP ranging from 0.12 to 0.14, and produced between 5 and 6 kg of ice per square meter of collector. Analysing the temperature gradient within the adsorbent bed, the authors concluded that in order to improve the performance of this system, the heat transfer properties of the adsorber must be enhanced. This could be achieved by increasing the number of fins or using consolidated adsorbent.

An adsorption icemaker with the pair activated carbon–methanol, was tested in Burkina Faso by Buchter et al. [37]. The results of this prototype were compared to those obtained by Boubakri et al. [38,39] in Morocco, with a similar system, which was commercially produced in the 1980s by the French company BLM.

In order to solve the corrosion problem of sea water in the steel adsorber and simplify the operation of the ammonia system, a split heat pipe type two-bed adsorption icemaker test unit is designed and constructed in Shanghai Jiao Tong University (SJTU) [40]. The experimental set-up uses composite adsorbent of $CaCl_2$ and activated carbon to improve the adsorption performance. There exists mass recovery between two beds in this test unit. At the evaporating temperature of −15 °C, its average cooling power is 1.37 kW, corresponding COP is 0.41 and Specific Cooling Power (SCP) is 731 W/kg. The mass recovery process improved SCP and COP for the system by 15.5% and 24.1%, respectively. Heat transfer performance is also improved by the introduction of the split heat pipe. The average heat transfer coefficient for a whole cycle is 155.8 W/(m^2 °C). Currently the concept has been used to build a real icemaker, a demonstration type adsorption icemaker has been built in SJTU, the system has a cooling capacity of about 20–30 kg ice (−15 °C) per hour with a measured refrigeration COP about 0.2–0.3.

6.2. Solar air-conditioning

Saha et al. [41] experimentally investigated a double-stage, four-bed, non-regenerative adsorption chiller powered by solar/

waste heat sources between 50 and 70 °C. The prototype studied produced cold water at 10 °C and had a cooling power of 3.2 kW with a COP of 0.36, when the heating source and sink had a temperature of 55 and 30 °C, respectively. Flat plate collectors could easily produce hot water to regenerate the adsorbent of the chiller at this level of temperature.

An adsorption air-conditioning system was developed by Wang et al. [42] to be powered by heat sources with temperatures close to 100 °C. Evacuated tube collectors could be used to supply hot water at this level of temperature. The system had two adsorbers with 26 kg of carbon inside each, using methanol as a refrigerant. The COP and the SCP of this system were significantly influenced by the cycle time. The operation of the system with a cycle time of 30 min produced a COP of 0.15 and a cooling power of 3.84 kW while operation with a cycle time of 60 min produced a COP of 0.21 and cooling power of 3.03 kW. In both situations, the evaporation temperature was close to 6 °C. To improve the performance of the system, the authors changed the adsorbers to a tube and plate heat exchanger, keeping the same charge of carbon. In this new adsorber, the carbon was placed outside the tubes, between the plates. With this design, COP was 0.4 and cooling power was 3.80 kW. The experimental conditions in this case were: a heat source temperature of 100 °C, an evaporation temperature of 10 °C, a condensing temperature of 24 °C and a cycle time of 50 min.

In order to overcome the intermittent character of a single bed solar adsorption cycle, a novel model of the combined cycle of a solar-powered adsorption–ejection refrigeration system was established by Li et al. [43]. The estimated thermal COP is about 0.4 under the following operating conditions: condensing temperature 40 °C, evaporating temperature 10 °C, regenerating temperature 120 °C and desorbing temperature 200 °C, using zeolite 13×–water as the working pair.

A silica gel–water 10 kW adsorption chiller has been developed and its performance is tested in detail in SJTU [44,45]. The experimental results show that the refrigerating COP of the chiller could reach 0.4 if it is powered by 85 °C hot water with 10 °C chilled water outlet temperature and 30 °C cooling water temperature. The results confirm that this kind of adsorption chiller is an effective refrigerating machine. Also it is effectively driven by a low-grade heat source. Therefore, its application to the low-grade heat source is attractive. This silica gel–water adsorption chiller has been commercialized and used in the green building project in Shanghai [46], solar cooling for grain storage [47], and also micro-CCHP systems [48].

Nunez et al. [49] developed and tested a silica gel–water adsorption chiller with nominal cooling power of 3.5 kW. It had two adsorbers, each one filled with 35 kg of adsorbent. The chiller operated at generation temperatures between 75 and 95 °C, heat sink temperatures between 25 and 35 °C, and evaporation temperature ranging from 10 to 20 °C. The COP varied from 0.4 to 0.6, according to the experimental conditions. The authors compared the performance of this chiller to the performance of the Nishiyodo NAK 20/70 adsorption chiller and to the Yasaky WFS SC-10 absorption chiller. The figures of merit compared were the COP and the cooling power density at different reduced temperatures. This temperature was defined as the ratio between the adsorber–evaporator temperature gap and the adsorber–condenser temperature gap during the adsorption and desorption phases, respectively.

Restuccia et al. [50] developed an adsorption chiller that employed silica gel impregnated with $CaCl_2$ as sorption material. This adsorbent was chosen because it has high sorption ability (up to 0.7 kg of water per kg of dry sorbent) and most of the water content can be desorbed at generation temperatures between 90 and 100 °C. When the condensation temperature was 35 °C, the COP of the chiller was close to 0.6 in the range of generation temperatures from 85 to 95 °C, but it varied between 0.3 and 0.4 when the condensation temperature was 40 °C. The evaporation temperature during these experiments was 10 °C. The SCP was 20 W/kg when the generation temperature was 95 °C and the condensing temperature was 40 °C.

7. Solar air-conditioners in real applications

Xia et al. [51] applied for a patent of a silica gel–water adsorption chiller driven by a low temperature heat source that was used to cool a grain depot in the Jiangsu Province, China. This chiller has two identical chambers and a second stage evaporator with methanol as working fluid. Each chamber contains one adsorber, one condenser and one evaporator (the first stage evaporator). There is also a mass recovery tube between the two chambers. The solar-powered heating unit produces hot water that regenerates the adsorption bed of the chiller. The cooling effect obtained during the adsorption phase of the chiller is transferred to the grain depot through a fan coil unit. The available hot water provided by the solar collectors has a temperature between 60 and 90 °C. Field measurements showed that under a daily solar radiation between 16 and 21 MJ/m^2, the chiller can supply cold air with temperatures from 14 to 22 °C.

Two chillers, similar to the one above, but with a higher nominal capacity, are used in the air-conditioning system of a "green" building located in the Shanghai Research Institute of Building Science. The chillers were installed in the equipment room located on the top floor of the building, and they operate from 9:30 AM to 4:30 PM. Experiments performed when the daily solar radiation was 19.2 MJ/m^2, showed that the chillers had an average cooling power of about 12 kW, with corresponding cycle and solar COP of 0.28 and 0.09, respectively. The silica gel beds of these chillers are regenerated by hot water at 65 °C, produced in 170 m^2 of U-type evacuated tube collectors. The average efficiency of the solar collectors is about 36%. If the hot water supplied to the chiller reaches approximately 85 °C, which could be expected on sunny summer days, the average daily cooling power could be close to 15 kW.

European project Climasol [52] presented examples of buildings that already use solar-powered sorption air conditioners. The examples presented include applications of solid sorption chillers and solid desiccant systems. Some of the chillers were installed in a university hospital located in Freiburg, Germany, and in the cosmetic company Sarantis S.A., in Greece.

The system in the university hospital has 230 m^2 of evacuated tube collectors that produce hot water used to drive an adsorption chiller with a 70 kW cooling power during summer, or to pre-heat the air during winter. The COP of this chiller is about 0.6 and the efficiency of the solar collectors is 32%.

The system located in the cosmetic company uses 2700 m^2 of flat plate collectors to produce hot water with a temperature of 70–75 °C. This water is used during the summer to power two adsorption chillers with 350 kW of cooling power each. The COP of these chillers is about 0.6. In winter, the hot water is used for heating purposes inside the buildings.

8. Issues

The adsorption systems must have their size and cost reduced to become more commercially attractive. The most promising alternatives to achieve these goals include the enhancement of the internal and external heat transfer of the adsorber to increase the SCP, and the improvement of the heat management to increase the COP. The main technologies to enhance the external heat transfer in the adsorber are related to the increase of the heat exchange area, the use of coated adsorbers and the utilization of heat pipe

technology. To improve the internal heat transfer, the most suitable option is the employment of consolidated adsorbents.

8.1. Extended surfaces

Several types of extended surfaces can be considered, such as finned tubes, plate heat exchangers and plate–fin heat exchangers. The drawback of this technology is that it increases the thermal capacity of the adsorber; therefore, extended surfaces heat exchangers require efficient heat management to produce reasonable COPs. Furthermore, this solution should be avoided if the operation pressure is very low and the Knudsen effect can occur [28].

8.2. Coated adsorbers

The utilization of coated adsorbers is particularly suited for applications where high COP is not as important as high SCP. This technology consists in the increase of the wall heat transfer coefficient by the effective decrease of the contact thermal resistance between the heat exchange surface and the adsorbent. The main disadvantage of using coated adsorber is the very high ratio between the inert mass and the adsorbent mass, which spoils the COP. In order to overcome this drawback, a very effective heat management is required.

8.3. Consolidated and composite adsorbents

Consolidated adsorbent with high thermal conductivity can be considered as the most promising alternative to enhance the heat transfer within the adsorber. Poyelle et al. [53] used a consolidated composite compound made from zeolite and expanded graphite with enhanced heat transfer properties in their experiments and achieved a SCP four times higher than that obtained using zeolite pellets.

Guilleminot et al. [54] studied a consolidated composite compound made from a mixture of zeolite and metallic foam. The compound produced from zeolite and copper foam had a thermal conductivity of 8.0 W/m K, which was 22 times higher than that of consolidated zeolite. The authors stressed the importance of the metallic foam material used in the compound, as the thermal conductivity obtained with the compound manufactured from zeolite and nickel foam was only 1.7 W/m K.

Wang et al. [40] developed a consolidated compound made from a mixture of $CaCl_2$ and activated carbon. Experiments performed by the authors showed that the utilization of this compound could lead to a cooling density 35% higher than that obtained by the use of powder $CaCl_2$.

In general, consolidated adsorbents have lower mass transfer properties than granular adsorbents, which could lead to very low adsorption rates especially for refrigerants evaporating under atmospheric pressure, such as water or methanol. Thus, besides experiments to identify the thermal conductivity and the wall heat transfer coefficient of these compounds, experiments to identify their permeability must also be performed when a new consolidated adsorbent is formulated.

By controlling the compression pressure, and the mass ratio between the adsorbent and the inert material, it is possible to control the density of the final compound and its properties of heat and mass transfer.

8.4. Advanced cycles

The aim of the researches focused on advanced cycles with heat management is the increase of the COP, since in the conventional adsorption cycle, COP is usually smaller than 0.4 [55].

In the cycle with heat recovery, one adsorber, at the beginning of the adsorption phase, releases heat to a cold adsorber, which is starting the generation phase. Theoretically, this process can continue until the temperatures of both adsorbers are similar, but for practical reasons, it usually stops when the difference between the temperatures is within the range of 5–15 °C. Then, the adsorbers are connected to a heat sink and heat source, to finish, respectively, the adsorption and the generation process. Due to this heat management, about 35% of the total energy transmitted to each adsorber can be internally recovered, including part of the sorption enthalpy [56].

Besides the utilization of heat management cycles, it is possible to employ refrigerant mass recovery between two adsorbent beds to enhance effectively both the cooling power and the COP. Szarzynski et al. [57], analysed cycles with refrigerant mass recovery and concluded that the SCP could be increased by about 20%.

Wang [58] compared the COP of adsorptions systems with and without mass recovery and found that the former could produce a COP from 10% to 100% higher than the latter. The difference between the COPs was higher at lower generation temperatures.

Although the advanced cycles can increase the performance of the adsorption systems, the complexity of the system also increases. Therefore, among the studied advanced cycles, the mass recovery cycle seems to be one of the most cost effective ways to improve both COP and SCP.

9. Challenges to commercialization

The principal challenge for adsorption refrigerators powered by solar energy is to overcome several failed attempts to commercialize them. Commercialization of the silica gel/sulphur dioxide refrigerator in the 1930s and the activated carbon–methanol refrigerator in 1960, both of which used a fossil fuel based heat source, were unsuccessful because of the emergence of more efficient vapour compression refrigerators using cheap conventional energy, including electrical energy. More recently, the commercially tried adsorbent/adsorbate combination of activated carbon–methanol and zeolite–water refrigerators proved to be technically successful but too expensive to penetrate the market. The BLM company of France and Comesse Soudure of South Africa produced the activated carbon–methanol refrigerators. The Zeopower company of the USA manufactured the zeolite–water refrigerators. However, the unit price for the BLM system was considered too high to get a real market.

10. Conclusion

Although investment costs for adsorption chillers using silica gel are still high, the environmental benefits are impressive, when compared to conventional compressor chillers. The absence of harmful or hazardous products such as CFCs, together with a substantial reduction of CO_2 emissions due to very low consumption of electricity, creates an environmentally safe technology. Low temperature waste heat or solar energy can be converted into a chilling capacity as low as 5 °C with minor maintenance costs.

Nevertheless, some crucial points in the development of sorption systems still exist and those are closely connected to the low specific power of the machine and the investment costs.

Recently, more close attention was paid to the development of combined systems of solar cooling and heating in order to make use of all types of energies rationally. All these works will be of great favour to the development of the solar sorption refrigeration system.

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